Ionospheric TEC Assimilation and Now-casting System over China

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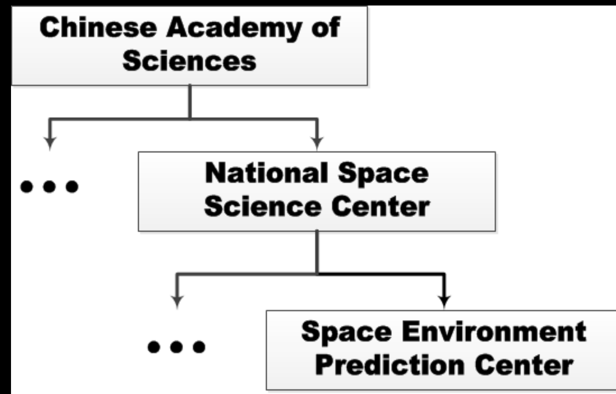
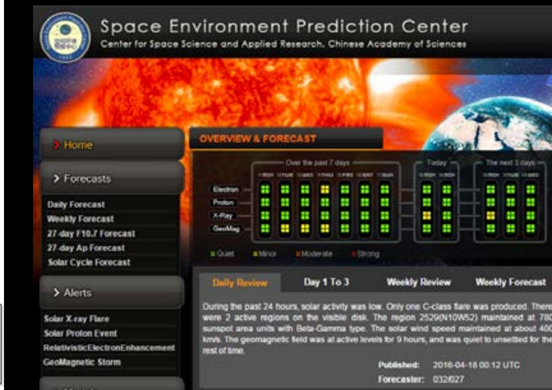




NSSC Established → **SEPC Constructed** → **Issuing Operational Services**

1958

The National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS) was established in 1958 with the mandate to develop the first artificial satellite of China, the DFH-1.

1992

To meet the space weather requirements for China's space missions, SEPC was established in 1992 in NSSC, CAS, and became the 1st professional organization providing space weather services in China.

1998

In 1998, SEPC set up the first generation of an operational space weather forecasting system, and since then started to issue operational space weather forecasting services via internet 365 days/year.

Contents of Basic Space Weather Services

- **Space Environment Nowcasts**
  - ➢ Sunspot Number/F10.7 index/solar X-ray flux
  - ➢ IMF Solar wind speed & density
  - ➢ High energy electron/proton flux
  - ➢ Planetary K-index
- **Space Environment Reviews and Forecasts**
  - ➢ Presenting analyses of current conditions and developing trends of solar and geomagnetic activities
- **Space Weather Event Alerts**
  - ➢ Solar X-ray Flare
  - ➢ Solar Proton Event
  - ➢ Relativistic Electron Enhancement
  - ➢ Geomagnetic Storm

International Cooperation of SEPC/NSSC

- The **International Space Environment Services (ISES)** is a space weather service organization. The mission of ISES is to improve, coordinate, and deliver operational space weather services.
- ISES has 16 Regional Warning Centers and 4 Associate Warning Centers
- SEPC/NSSC is now **an Associate Warning Center of ISES**

IPS (Australia)
KSO (Austria)
SIDC (Belgium)
EMBRACE (Brazil)
CSWFC (Canada)
SEPC (China)
SAPC (China)
IAP (Czech Republic)
NPL (India)
NICT (Japan)
KSWC (Republic of Korea)
SCiESMEX (Mexico)
SRC (Poland)
IAG (Russia)
SANSA (South Africa)
LSWC (Sweden)
MOSWOC (UK)
SWPC (USA)
ESA (Noordwijk)

Space weather cooperation efforts made by SEPC/NSSC and other ISES members
Enhance the exchange of self-monitoring data and relevant information of space weather
Establish standardized verification methods for space environment forecasting services
Improve collaboration on verification and validation of space weather operational models

Services for Manned Space Flight Missions of China

1999 — Nov.20,Shenzhou I

2001 — Jan. 10 Shenzhou II

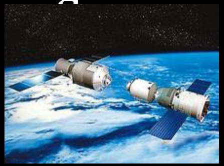
2002 — Mar.25 Shenzhou III

2003 — Dec. 30 Shenzhou IV
Oct.15 Shenzou V
The first manned spaceship

2005 — Oct.12 Shenzhou VI
Multi-person and multi-day

2008 — Sep.25 Shenzhou VII
EVA, Space-related scientific tests

2011 — Sep.29 Tiangong I
Nov.1 Shenzhou VIII
Rendezvous and docking



2012 — June 16 Shenzhou IX
Manual rendezvous and docking

2013 — June 11 Shenzhou X

2016 — Sep 15 Tiangong II
Oct 17 Shenzhou XI

SEPC/NSSC has supplied space weather service in each step of China Manned Space Program for 11 Shenzhou space ships and Tiangong I & II.

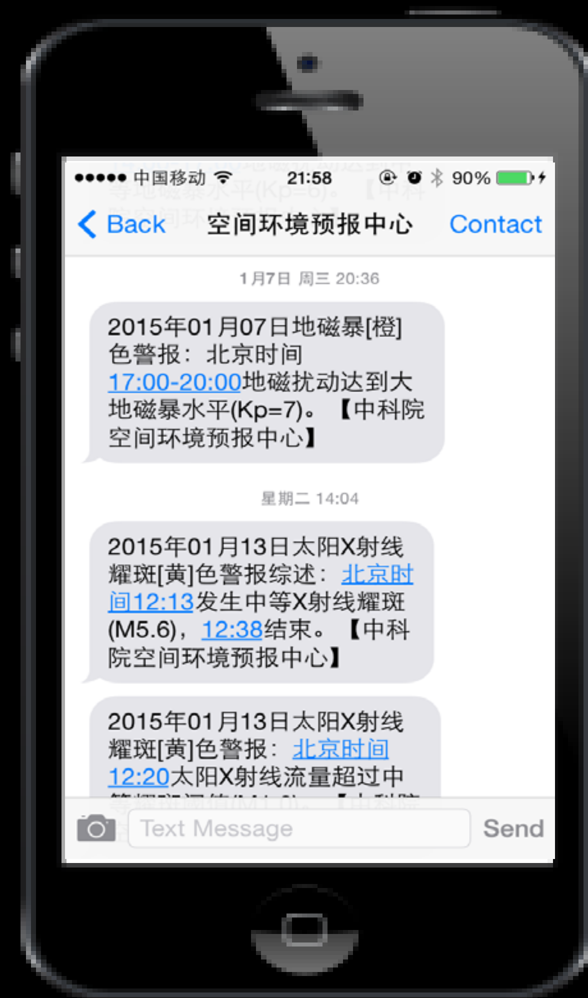
Delivery of Space Weather Services for Public

http://eng.sepc.ac.cn

- Website
  - General public
- Text message
- App (IOS + Android)
- Microblog (Twitter)

Delivery of Space Weather Services

- Website
- Text message
  - Real time alerts
- App (IOS + Android)
- Microblog (Twitter)



Delivery of Space Weather Services

- **Website**
- **Text message**
- **App (IOS + Android)**
- **Microblog (Twitter)**

iPhone

Android

Mobile App “e SpaceWx”

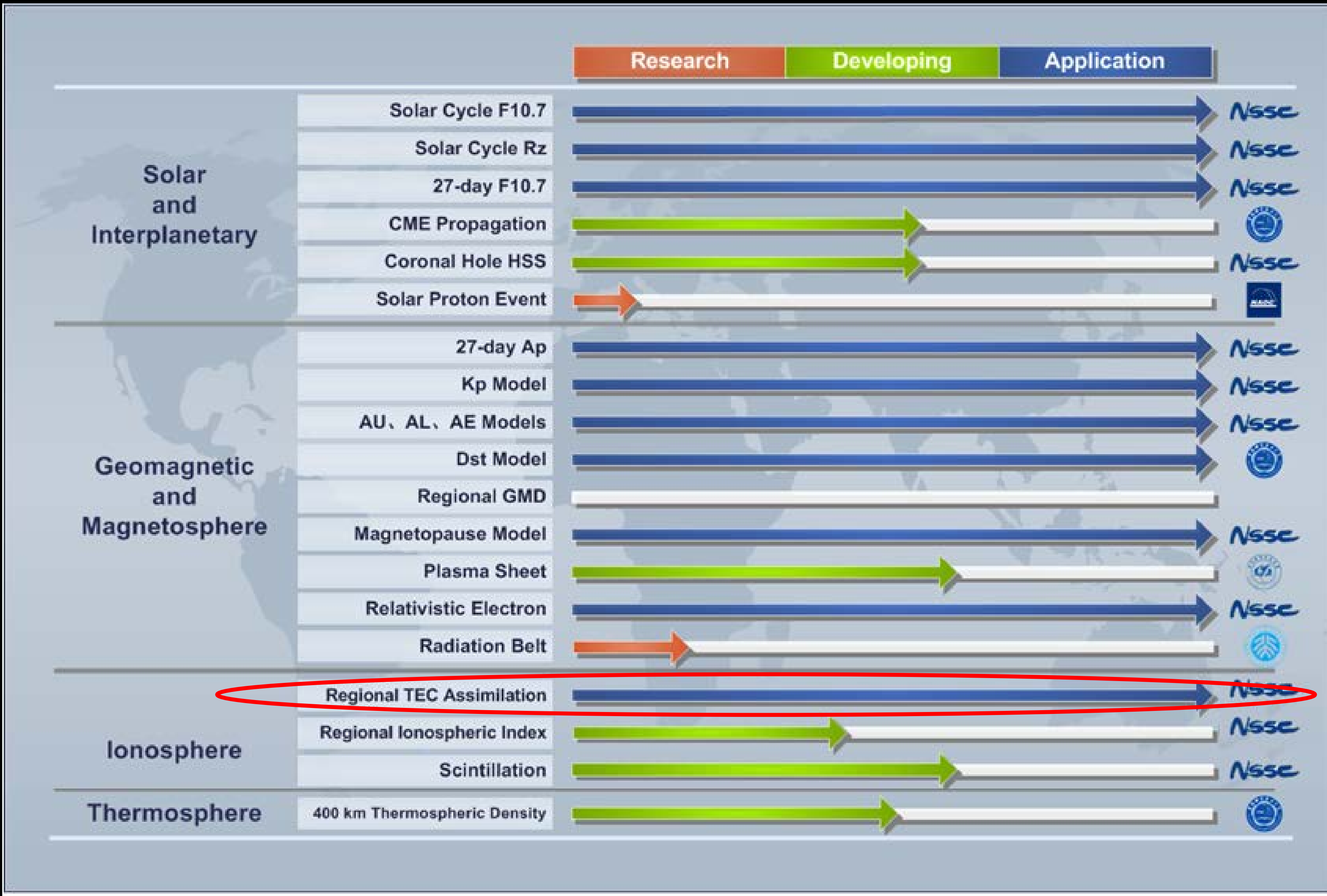
Delivery of Space Weather Services

- Website
- Text message
- App (IOS + Android)
- Microblog (Twitter)
  - Real time forecast
  - Interaction (>14k followers)

http://weibo.com/spaceweather

http://t.qq.com/sepc2013

Space Weather Operational Models

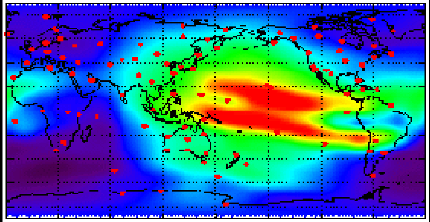


TEC GIM/RIMs

Who provides Global Ionospheric Maps?

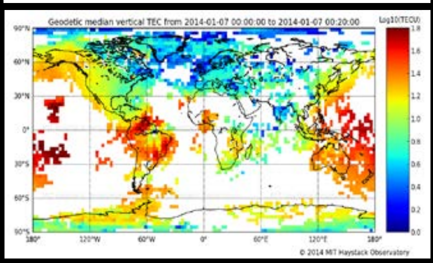
- Center for Orbit Determination of Europe **(CODE)**
- Jet Propulsion Laboratory **(JPL)**
- European Space Agency **(ESA)**
- Polytechnical University of Catalonia **(UPC)**

2.5º *5º *1 h

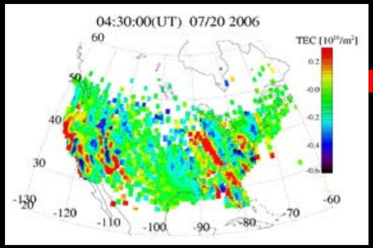


- MIT Automated Processing of GPS **(MAPGPS)**

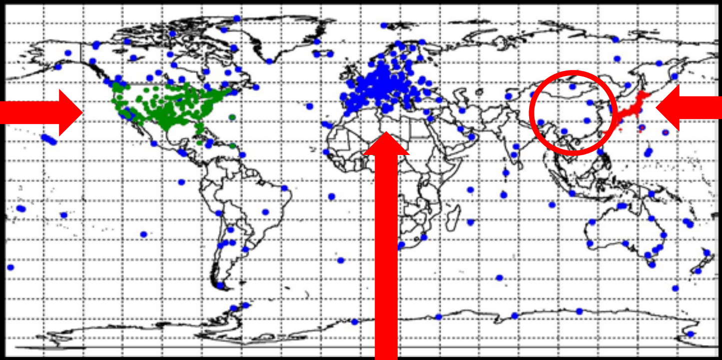
1º *1º *5 min



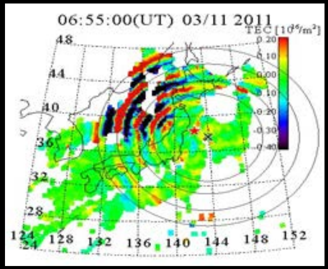
Regional Ionospheric Maps and real-time TEC product?



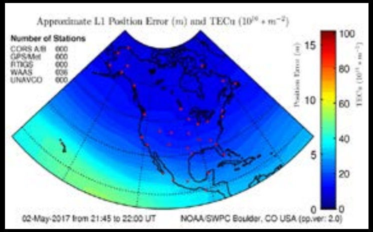
N. America
~2,700 Receivers
[Tsugawa et al., 2007]



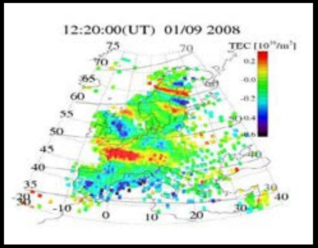
Europe
~1,200 Receivers
[Otsuka et al., 2012]



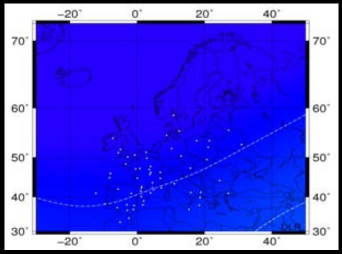
Japan
~1,200 Receivers
[Tsugawa et al., 2011]

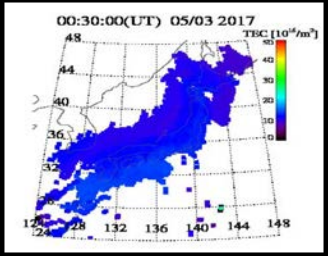


NATEC (NOAA/SWPC)



Europe TEC (ESA)





GEONET TEC (NICT)

Ionospheric modeling via data assimilation

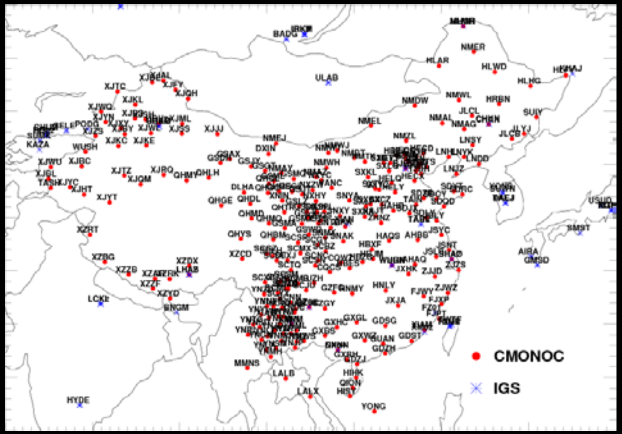
- **The data assimilation technique has been proved as an effective and efficient way of specifying ionosphere, which is implemented by using certain optimization schemes to incorporate measurements into background models.**
- **There are three essential elements in data assimilation techniques:**
  - **the background model (IRI) and observations (TEC data)**
  - **the optimization assimilation algorithm**
  - **the associated error covariance matrices**

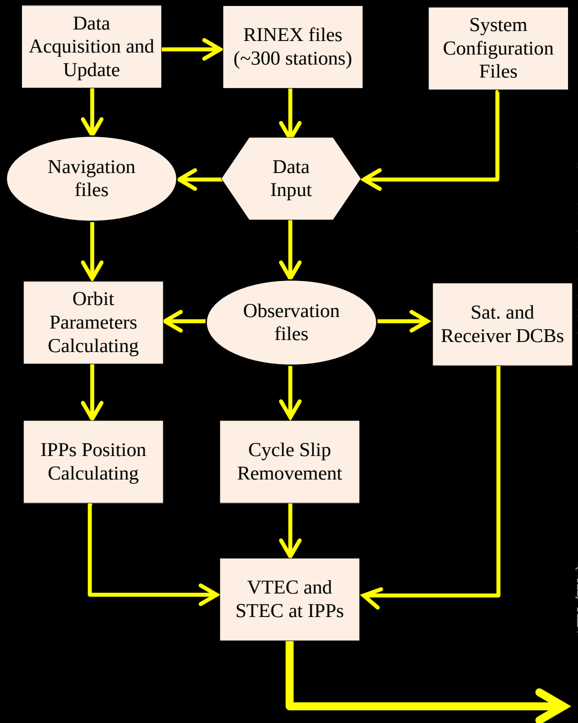
- **Typical Data Assimilation Models/Products**
  - **Utah State University: Global Assimilation of Ionospheric Measurements (USU GAIM)**
  - **University of Southern California and the Jet Propulsion Laboratory: Global Assimilative Ionospheric Model (USC/JPL GAIM)**
  - **University of Texas: Ionospheric Data Assimilation Three/Four-Dimensional algorithm (IDA3D/IDA4D)**
  - **NOAA/SWPC: U.S. Total Electron Content (US-TEC)**

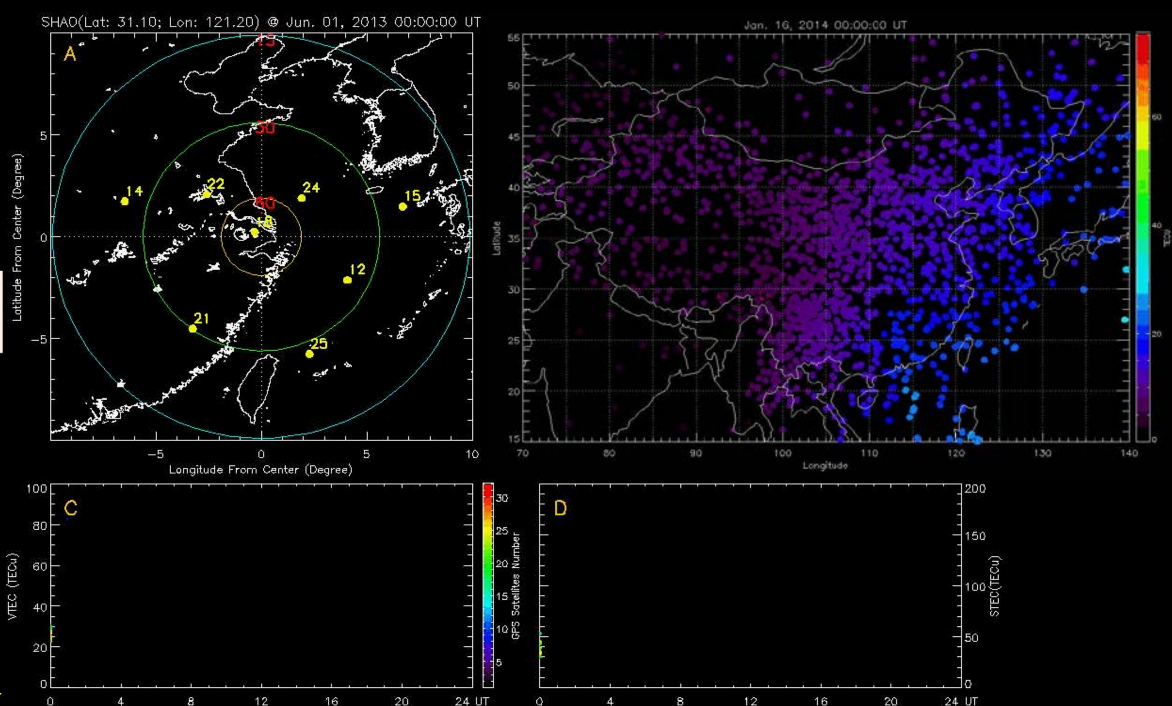
GNSS Data Processing & TEC Derivation

- GNSS Receivers over China and adjacent areas (15°-55°N, 70°-140°E)

~300+ Receivers		
Crust Movement Observation Network of China (**CMONOC**)	International GNSS Service (**IGS**)	Space Environment Prediction Center (**SEPC**)
260+ Receivers	38 Receivers	9 receivers







Data assimilation method: 3DVAR

There are three essential elements in data assimilationtechniques:

- **the background model (IRI) and observations (TEC data)**
- **the optimization assimilation algorithm (3DVAR)**
- **the associated error covariance matrices**

3-Dimensional Variationa (3DVAR) is a statistical optimization method that seeks to minimize a cost function which represents the measure of the closeness between background model predictions and the measurements.

- Format of cost function $J(x)$

$$J(x) = \frac{1}{2}(x - x_b)^T P^{-1}(x - x_b) + \frac{1}{2}(y - Hx)^T R^{-1}(y - Hx),$$

- x: the state variable (the analyzed N_e)
- x_b: the background field (IRI estimation)
- P: the background error covariance matrix
- R: the observation error covariance matrix
- y: the observation vector (slant TEC)
- H: the observation forward operator (length that each satellite-receiver ray passes through every grid point)

Time Update ("Predict")

1. Project the state ahead
2. Project the error covariance

$$x_f(t_{n+1}) = x_b(t_{n+1}) + [x_a(t_n) - x_b(t_n)]e^{-\frac{\Delta t}{\tau}}$$

$$P_f(t_{n+1}) = P_b(t_{n+1}) + [P_a(t_n) - P_b(t_n)]e^{-\frac{2\Delta t}{\tau}}$$

Measurement Update ("Correct")

3. Update the estimate
4. Update the error covariance

$$x_a = x_f + P_f H^T [R + HP_f H^T]^{-1}(y - Hx_f)$$

$$P_a = P_f - P_f H^T [R + HP_f H^T]^{-1} HP_f$$

Setting of error covariance matrix

- The error covariance matrices *P and R are critical parameters in the assimilation process, and the effects of* 3DVAR objective analysis depend largely on the determination of these two factors. In a number of studies, *the observation error is assumed to be independent and proportional* to the square of the observation; the background error is also considered to be proportional to the square of state variable and is considered to have Gaussian correlations; the horizontal and vertical correlations are assumed to be independent and thus separable.

- **Error covariance matrices P and R**

$$P_{ij} = C_P x_b^i x_b^j e^{-(z_i - z_j)^2/(L_V^{ij})^2} e^{-d_{ij}^2/(L_H^{ij})^2},$$
$$R_{ij} = C_R \delta_{ij} y^2,$$

  - z: the altitude
  - d_{ij}: the horizontal great circle distance between grid points i and j
  - L_V: the ionospheric vertical correlation length
  - L_H: the ionospheric horizontal correlation length
  - C_P and C_R: User-configurable coefficients
  - δ: the Dirac delta function

- **Expression of ionosphere correlation length**

$$(L_V^{ij})^2 = L_z^i L_z^j,$$
$$\frac{1}{(L_H^{ij})^2} = \frac{cos^2(\alpha)}{L_\theta^i L_\theta^j} + \frac{sin^2(\alpha)}{L_\phi^i L_\phi^j},$$

  - α: azimuth between two grid points
  - L_θ: ionospheric meridional correlation length
  - L_ϕ: ionospheric zonal correlation length
  - L_z: ionospheric altitudinal correlation length

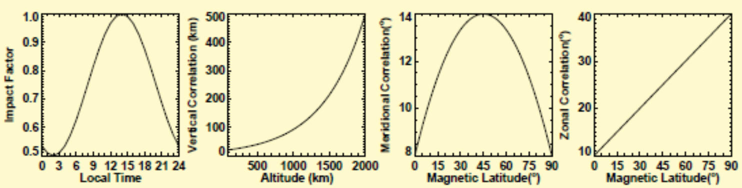
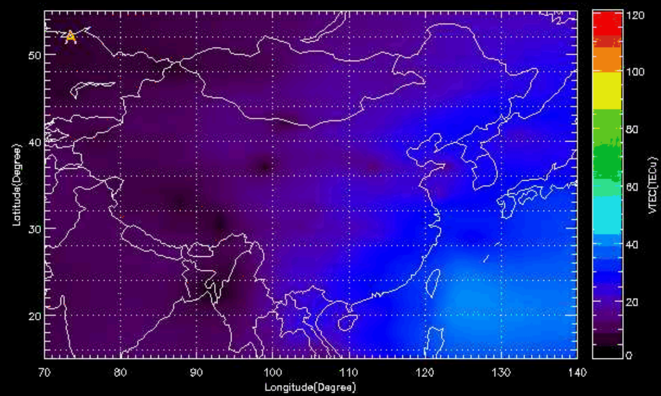
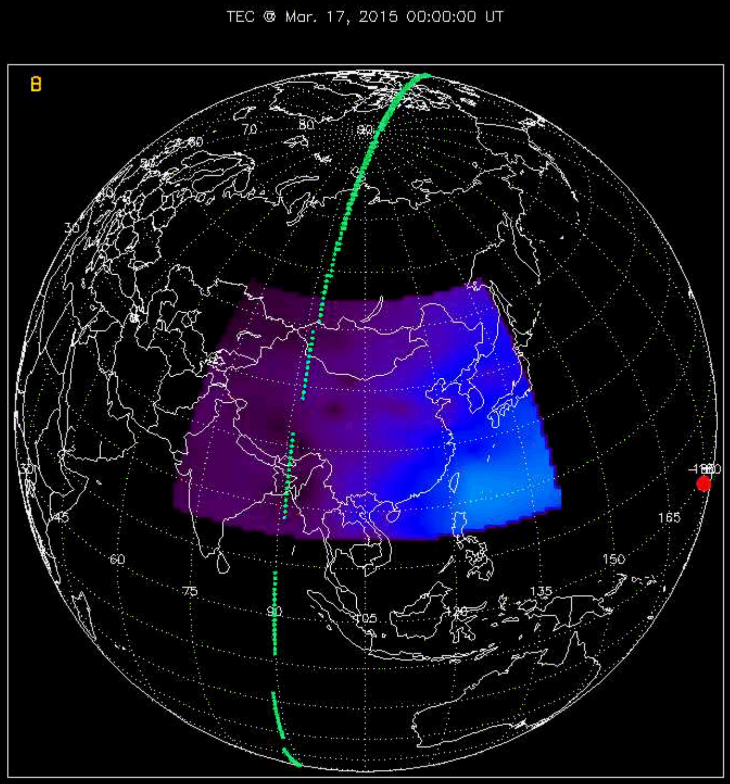
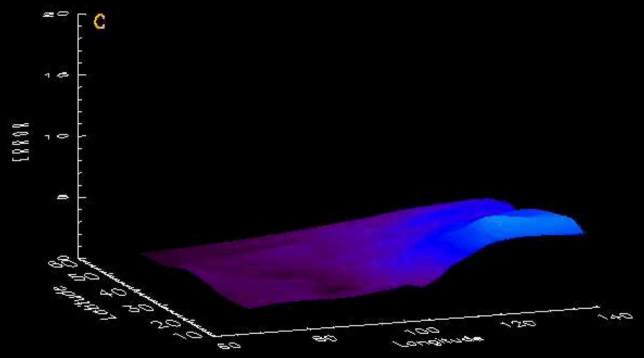


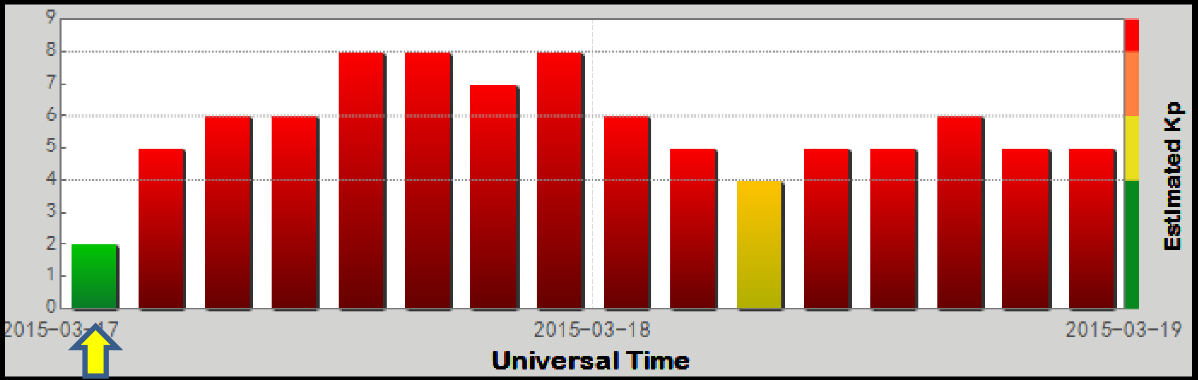
Figure 2: *Diurnal variation coefficients of ionosphere correlation length; vertical ionosphere correlation length with respect to altitude; meridional and zonal ionosphere correlation length with respect to magnetic latitude.*

Assimilation results: Geomagnetic storm and ionospheric storm on March 17-18, 2015

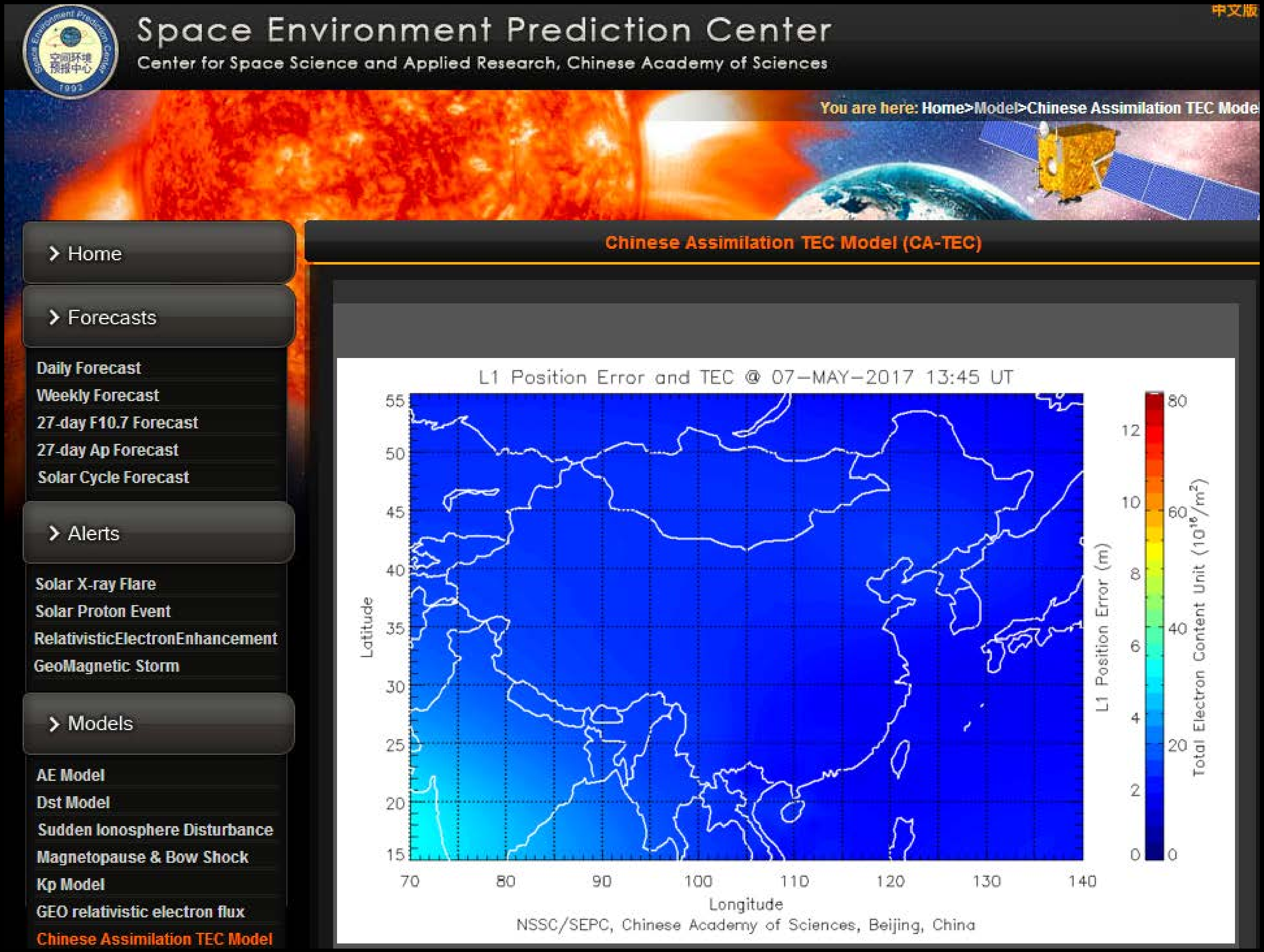








http://eng.sepc.ac.cn/TEC_eng.php



$1^o * 1^o * 15$ min driven by ~60 receivers

Summary

- First, the statistical analysis demonstrates that the data assimilation results pushes the climatological IRI model toward the observation. A general error reduction and accuracy improvement of 15-30% can be expected for quiet time assimilation, while the improvements under active conditions are more variable.
- Second, The regional gridded TEC maps are publicized online in quasi-real time with the resolution being $1^{o} \times 1^{o} \times 15$ min. It is the first ionospheric now-casting system in China based on data assimilation algorithm, which can be used in providing accurate and effective specification of regional ionospheric TEC and error correction for satellite navigation, radar imaging, shortwave communication, and other relevant applications.

Reference

- Aa, E., W. Huang, S. Yu, S. Liu, L. Shi, J. Gong, Y. Chen, and H. Shen (2015), A regional ionospheric TEC mapping technique over China and adjacent areas on the basis of data assimilation, J. Geophys. Res. Space Physics, 120, 5049-5061, doi:10.1002/2015JA021140.

- Aa, E., S. Liu, W. Huang, et al. (2016), Regional 3-D ionospheric electron density specification on the basis of data assimilation of ground-based GNSS and radio occultation data (2016). Space Weather, 14, 1–16, doi:10.1002/2016SW001363.

Thank You !